Earth Surface Processes and Landforms
Earth Surf. Process. Landforms **24**, 557–562 (1999)

TECHNICAL COMMUNICATION

A CROSS-SCALE COMPARISON OF DRAINAGE BASIN CHARACTERISTICS DERIVED FROM DIGITAL ELEVATION MODELS

ZHI-YONG YIN[1]* AND XINHAO WANG[2]
[1]*Department of Geography, Georgia State University, Atlanta, GA 30303, USA*
[2]*School of Planning, University of Cincinnati, Cincinnati, OH 45221, USA*

Received 3 September 1997; Revised 22 October 1998; Accepted 5 January 1999

ABSTRACT

The feasibility of using small-scale digital elevation models (DEMs) to extract various drainage basin characteristics was evaluated by comparing basin parameters derived from the 1:250 000 DEMs with those from the 1:24 000 DEMs. Twenty basins ranging approximately from 150 km^2 to 1000 km^2 in West Virginia, a geologically complex region, were examined in this study. The basin parameters examined included those commonly used in hydrology and geomorphology such as elevation, slope, stream length, drainage density, relief ratio and ruggedness number. Our results suggested that the 1:250 000 DEMs can provide accurate estimates for elevation-based and stream-length-based basin parameters, but not for slope-based parameters. After examining the differences between the DEM-derived basin parameters from the two different scales, we found that the performance of the 1:250 000 DEMs was not significantly influenced by basin size, while terrain complexity seems to be an important factor of accuracy of the estimated basin parameters. Copyright © 1999 John Wiley & Sons, Ltd.

KEY WORDS: digital elevation models (DEM); scale; drainage basin parameters; drainage networks; geographical information systems (GIS)

INTRODUCTION

Starting with R.E. Horton (1945) and A.N. Strahler (1957, 1958, 1964), basin physiographic characteristics have been considered as important indices of surface processes. These parameters have been used in various studies of geomorphology and surface-water hydrology, such as flood characteristics, sediment yield and evolution of basin morphology. More recently, terrain characterization has become an important part in modelling surface processes (Nogami, 1995). From the time when the methodology of basin analysis was first developed, it has been known for its tediousness and labour intensity. Most measurements must be made manually on large- to medium-scale topographic maps. This shortcoming has seriously limited the potential applications of drainage basin characteristics in hydrology and geomorphology.

Since the mid-1980s, with increasing popularity of geographic information systems (GIS) technology and availability of digital elevation models (DEMs), the potential of using DEMs in studies of surface processes has been widely recognized (Moore *et al.*, 1992; Wharton, 1994). However, even with today's computing technology, processing large-scale DEMs can easily reach the limit of computing power and storage space for most PC-based and some workstation-based systems. The purpose of this study is to evaluate the feasibility to substitute the US Geological Survey (USGS) 1:24 000 (24K) DEMs with the USGS 1:250 000 (250K) DEMs in estimating some of the most commonly used drainage basin parameters (Ritter *et al.*, 1995, p.152). We also investigated the effect of basin size and terrain complexity on the accuracy of the estimated basin parameters.

* Correspondence to: Dr Z.-Y. Yin, Department of Geography, Georgia State University, Atlanta, GA 30303, USA. Email: gegzyy@panther.gsu.edu

CCC 0197-9337/99/060557–06 $17.50

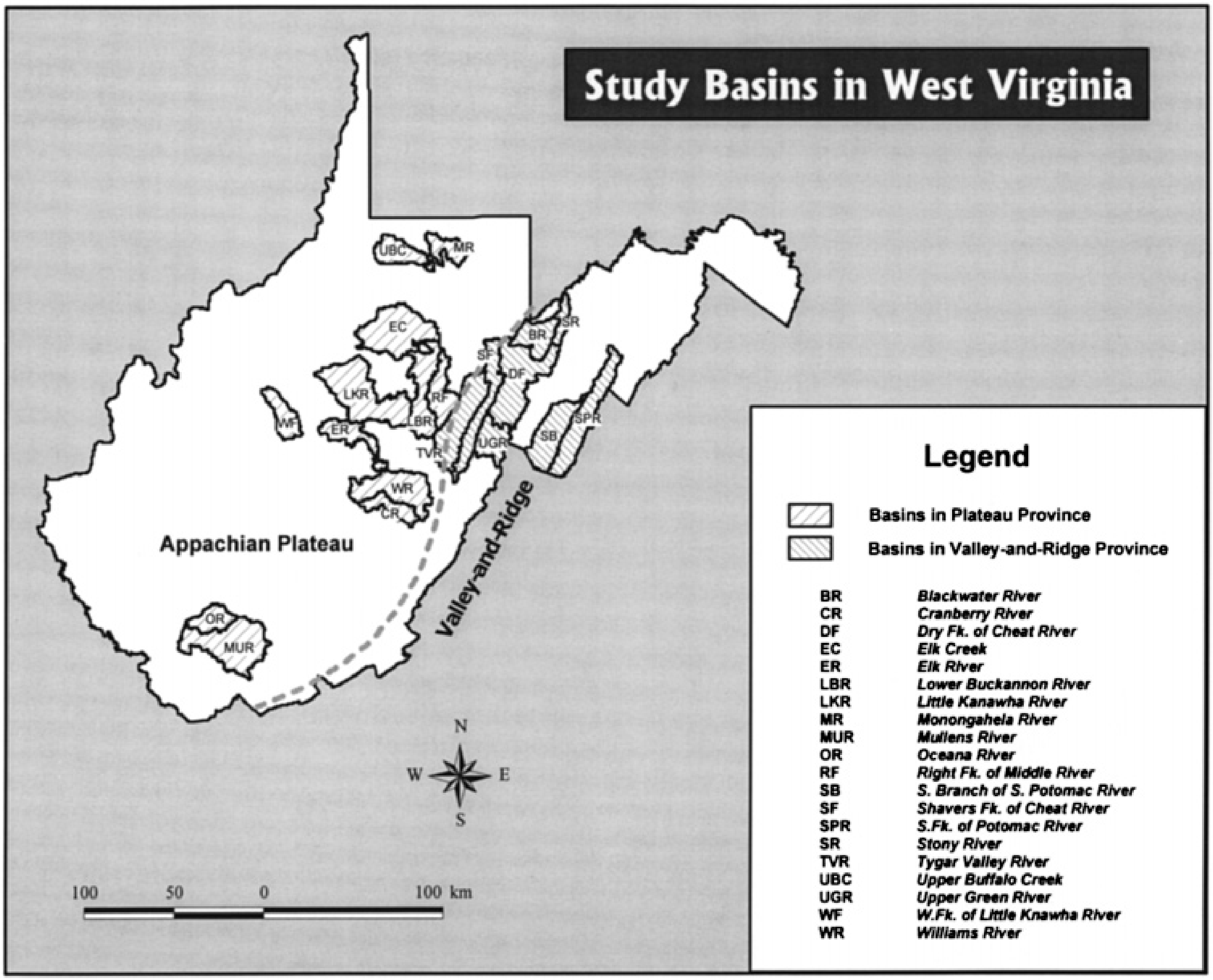

Figure 1. Drainage basins examined in this study. The dashed line is the approximate border between the Appalachian Plateau and Valley-and-Ridge physiographic provinces

DATA

We selected 20 drainage basins in West Virginia, ranging in size from 153 km^2 to 1017 km^2 (Figure 1). The State of West Virginia is located in the middle section of the Appalachian Highlands. The western part of the state is in the Appalachian Plateau Province, characterized by eroded horizontal and slightly dipping sedimentary strata. The eastern part of the state is in the Valley-and-Ridge Province, characterized by extensive valley-and-ridge topography with relief up to about 1000 m. The underlying geologic structures are mostly eroded folds composed of sedimentary rocks of various ages (Mills *et al.*, 1987). Stream and watershed data developed from the USGS 1:100 000 (100K) Digital Line Graph (DLG) were used as the basis of comparison for the DEM-derived drainage networks and to define the boundaries of the selected basins. All digital data were obtained from the West Virginia Environmental Protection Department.

METHODS

ARC/INFO (ESRI, Redlands, CA) was used to process the DEM data. The cell size was 30 m for the 24K and 3 arc-seconds (approximately 92 m) for the 250K DEMs. To generate stream networks, we first needed to calculate the flow direction based on the DEMs. Then flow accumulation was determined, where the cell values represented the number of cells upstream from this specific cell, or the upstream drainage area for each grid cell. It was necessary to specify a threshold cell number value corresponding to the minimum upstream drainage area to maintain the smallest stream segment, which influences the total stream length and details of stream networks. We identified a threshold cell number with which the 24K DEM-derived total stream length was equal to the 100K stream length by a trial-and-error approach. Then we determined the threshold cell number for the 250K DEM based on the assumption that the minimum area required to support the smallest stream segment is the same at both scales. This approach ensured that the stream networks generated from DEMs of the two different scales were comparable.

RESULTS AND DISCUSSION

Visual evaluation of the drainage networks

Apparently, the DEM-generated networks matched closely to the 100K streams (Figure 2). One major difference was that the DEM stream networks tended to be shorter in headwater areas, but they contained more first-order streams that were not shown in the 100K stream networks. This is because the 100K networks strictly display watercourses while the DEM networks are entirely determined by topography. When the 24K and 250K networks were examined, the two matched closely to each other. Because of lower spatial and vertical resolutions, the 250K networks appeared as short straight segments while the 24K networks displayed a higher degree of detail. However, we noticed that within the predetermined drainage basins, seven basins had broken drainage networks at either the 1:24 000 or 1:250 000 scale.

Comparison of basin parameters

Table I contains the results of paired Student *t*-test for the 20 basins. The differences between the parameter mean values at the two scales were statistically significant for all basin parameters. The 250K DEMs underestimated the mean maximum basin elevation and overestimated mean minimum basin elevation. Obviously, some high or low elevation points were simply missed due to the larger ground resolution cell size of the 250K DEMs. The 250K also underestimated the mean basin elevation. Regression analyses, however, indicated that the 250K DEMs can provide very good estimates to elevation-based parameters, such as mean, maximum and minimum basin elevations, and basin relief (Table II). The intercepts of the regression equation were not significantly different from zero and the regression coefficients were quite close to 1·0. The R^2 values were higher than 0·98, indicating almost perfect linear relationships.

Although we used 100K stream length as the standard in generating drainage networks, the total stream length and main stream length extracted from the 250K DEMs were still shorter than those derived from the 24K DEMs (Table II). This can be attributed to a lower vertical resolution of the 250K DEMs. Directly related to this was the underestimation of drainage density by the 250K DEMs, since the same basin area was used in the calculation. However, the 250K DEMs overestimated relief ratio, a measure of average gradient along the mainstream channel. Apparently, the 250K DEMs underestimated both basin relief and main stream length, but the latter was underestimated more than the former parameter. Again, regression analyses showed that 250K DEMs can be used to provide accurate estimates of relief ratio, ruggedness number, and the stream lengths. For drainage density, however, the intercept was significantly different from zero, and regression coefficient was not as close to 1·0 as those previously mentioned parameters (Table II).

The 250K DEMs considerably underestimated the slope parameters compared with the 24K DEMs (Table I). The impact of lower spatial and vertical resolutions of the 250K DEMs was most prominently reflected in the slope parameters because slope was calculated as a function of the elevations of neighbouring grid cells. The R^2 values indicated that 250K DEMs could not make accurate estimates for the slope parameters. Thus,

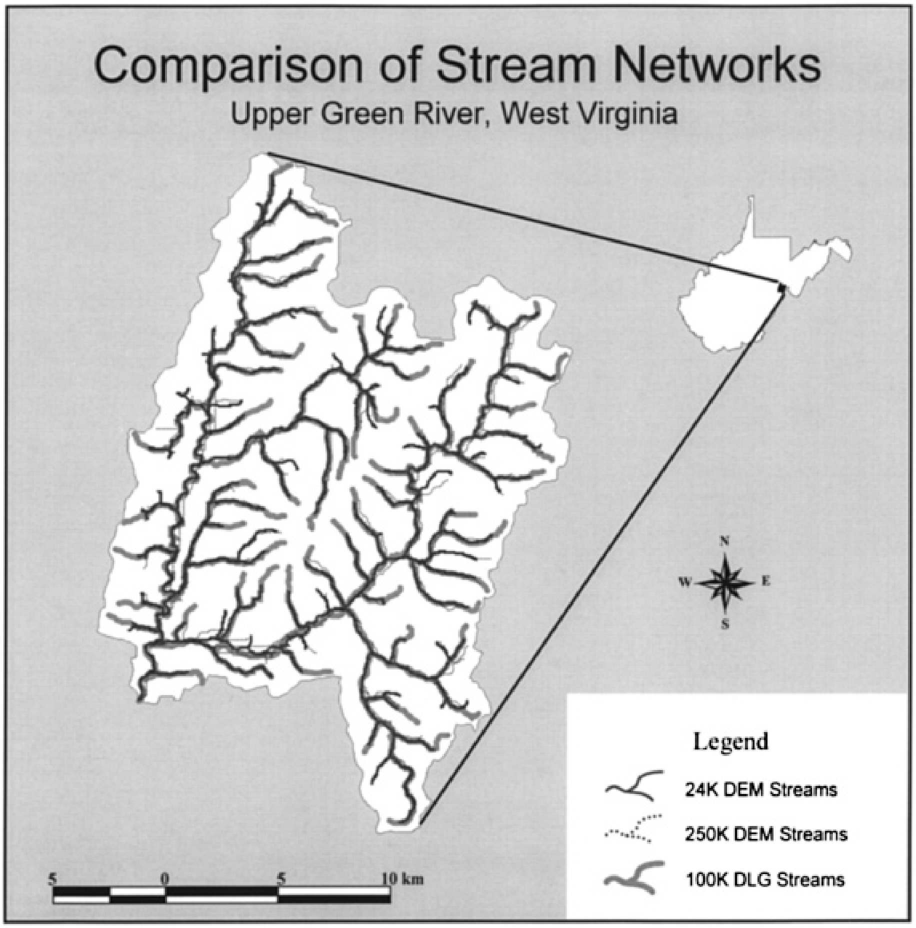

Figure 2. Comparison between the stream networks generated from the DEMs and the 100K DLG network

Table I. Paired Student t-test on basin parameters

Basin parameter	24K Mean	250K Mean	t	p*	Sample size
Minimum elevation, E_{min} (m)	424·5	434·4	3·24	0·0043	20
Maximum elevation, E_{max} (m)	1128·0	1098·5	4·76	0·0001	20
Mean elevation, E_{mean} (m)	714·9	707·3	5·82	0·0001	20
Elevation standard deviation, E_{sd}	129·5	127·9	2·48	0·0226	20
Basin relief, H (m)	703·5	664·1	5·49	0·0001	20
Total stream length, L (m)	452855	420126	4·93	0·0001	20
Mainstream length, L_{main} (m)	65106	56709	5·38	0·0002	13
Mean slope, S_{mean} (%)	24·7	14·3	12·56	0·0001	20
Maximum slope, S_{max} (%)	160·7	83·6	7·75	0·0001	20
Drainage density, D (m/m^2)	0·0009	0·0008	6·19	0·0001	20
Relief ratio, R_h	0·0112	0·0119	−3·12	0·0088	13
Ruggedness number, R_n	0·5963	0·5184	8·84	0·0001	20

* Significance level or the probability for the null hypothesis that there is no difference between the parameters at the two scales.

Table II. Regression analysis on basin parameters

Variable	Parameter*	Value	P†	R^2	N
E_{min}	A	−12·134	0·1861	0·9936	20
	B	1·0051	0·0001		
E_{max}	A	28·65	0·2134	0·9933	20
	B	1·0008	0·0001		
E_{mean}	A	6·2821	0·1270	0·9995	20
	B	1·0019	0·0001		
H	A	39·029	0·0964	0·9823	20
	B	1·0006	0·0001		
L	A	8136·9	0·5757	0·9852	20
	B	1·0585	0·0001		
L_{main}	A	−850·62	0·8393	0·9634	13
	B	1·1631	0·0001		
S_{mean}	A	7·7855	0·0120	0·6920	20
	B	1·1873	0·0001		
S_{max}	A	−14·043	0·6858	0·6082	20
	B	2·0898	0·0001		
D	A	0·0002	0·0013	0·9032	20
	B	0·8303	0·0004		
R_h	A	−0·00002	0·8348	0·9612	13
	B	0·9523	0·0001		
R_n	A	0·0491	0·0879	0·9617	20
	B	1·0558	0·0001		

* A, intercept; B, regression coefficient or slope
† Significance level or the probability for the null hypothesis that the regression coefficient is not different from zero

the 250K DEMs should be used to derive regional average values of the slope parameters for multiple basins, but not for individual basins.

Potential sources of errors

The errors were calculated as the differences between the 24K and 250K basin parameters. As the basin size varies from approximately 150 km^2 to 1000 km^2, one might expect that with increasing basin size, the performance of 250K DEMs would improve compared with the 24K DEMs. However, correlation analysis between the errors and basin size showed that basin size was not a major factor of accuracy (Table III). This finding suggested that the estimates based on 250K DEMs were fairly robust regardless of basin size. Additionally, we used the standard deviation of the 24K DEMs as the measure of terrain complexity for each individual basin. When we correlated the DEM standard deviation against the basin parameter errors, we found two significant correlations, one for stream length and another for drainage density (Table III). This finding implied that with increasing terrain complexity, the 250K DEMs would further underestimate stream length and drainage density, such as in the valley-and-ridge section of the Appalachians. The same is true for mean basin elevation, as indicated by a negative correlation coefficient ($r = -0{\cdot}3075$), although not as pronounced. On the other hand, the 250K DEMs may give better estimates for mean basin slope as terrain complexity increases, as indicated by a positive correlation coefficient ($r = 0{\cdot}3684$).

CONCLUSIONS

The differences between the mean parameter values derived from the two scales of DEMs were statistically significant, although in some cases the differences were quite small. For the elevation-based and some stream-length-based basin parameters (E_{mean}, E_{min}, E_{max}, H, L, L_{main}, R_h, R_n), more than 96 per cent of the variation in the 24K parameters were explained by the 250K parameters. Therefore, the 250K DEMs can be used to extract these basin parameters which will be transformed into more accurate estimates by applying a small correction factor. The procedure to extract these parameters is mostly influenced by the vertical

Table III. Correlation coefficients between basin parameter errors and basin size

Parameter error	Basin size		Terrain complexity		
	r	p*	r	p*	N
E_{min} (m)	−0·102	0·6687	−0·200	0·3982	20
E_{max} (m)	−0·105	0·6600	−0·055	0·8196	20
E_{mean} (m)	−0·152	0·5228	−0·308	0·1872	20
H (m)	−0·047	0·8430	0·038	0·8742	20
L (m)	−0·011	0·9649	−0·507	0·0226	20
L_{main} (m)	−0·325	0·2790	0·139	0·6509	13
S_{mean} (%)	−0·277	0·2379	0·368	0·1100	20
S_{max} (%)	−0·262	0·2650	−0·116	0·6254	20
D (m/m^2)	−0·009	0·9702	−0·504	0·0234	20
R_h	0·465	0·1094	0·316	0·2936	13
R_n	−0·071	0·7661	0·154	0·5157	20

* Significance level or probability for the null hypothesis that r is not different from zero

resolution of the DEMs, which has not been substantially reduced from that of the 24K DEMs. For drainage density (D), the 250K DEMs may still be used to obtain a relatively reliable result after the linear transformation based on the regression model, since the R^2 value was high (0·90). For mean and maximum basin slopes (S_{mean} and S_{max}), even after linear transformation based on regression models, the 250K DEMs can only provide fair estimates for basin slope parameters ($R^2 = 0{\cdot}6$ to 0·7). The best usage is for estimation of mean values for multiple basins. The relatively poor performance of the 250K DEMs should have resulted mostly from the reduced spatial resolution.

After examining two potential factors of errors of the basin parameters, we found that the differences between parameter estimates based on 250K DEMs and 24K DEMs were relatively insensitive to basin size, while the most profound effect of terrain complexity was on stream length and drainage density. With higher terrain complexity, the 250K DEMs would increasingly underestimate stream length and thereby drainage density compared with the 24K DEMs, but probably would provide improved estimates for the slope parameters. Further studies are required to investigate the generality of these relationships between the basin parameters derived from 24K and 250K DEMs. If such relationships can be reproduced in other regions with similar geologic and topographic settings, then the 250K DEMs can be used to enhance computing efficiency in drainage basin analysis.

REFERENCES

Horton, R. E. 1945. 'Erosional development of stream and their drainage basins; hydrophysical approach to quantitative morphology', *Geological Society of America Bulletin*, **56**, 275–370.

Mills, H. H., Bradenridge, G. R., Jacobson, R. B., Newell, W. L., Pavich, M. J. and Pomeroy, J. S. 1987. 'Appalachian mountains and plateaus', in Graf, W. L., (Ed.), Geomorphic Systems of North America, Centennial Special Volume **2**, Geological Society of America. 5–50.

Moore, I. D., Grayson, R. B. and Ladson, A. R. 1992. 'Digital terrain modelling: a review of hydrological, geomorphological, and biological applications', in Beven, K. J. and Mocre, I. D., (Eds) Terrain Analysis and Distributed Modelling in Hydrology, John Wiley & Sons, New York. 7–34.

Nogami, M. 1995. 'Geomorphometric measures for digital elevation models', *Zeitschrift fur Geomorphologie, Supplementband*, **101**, 53–67.

Ritter, D. F., Kochel, R. C. and Miller, J. R. 1995. Process Geomorphology, 3rd edn, Wm.C. Brown Publishers, Boston, 546 pp.

Strahler, A. N. 1957. 'Quantitative analysis of watershed geomorphology', *American Geophysical Union Transactions*, **38**, 913–920.

Strahler, A. N. 1958. 'Dimensional analysis applied to fluvially eroded landforms', *Geological Society of America Bulletin*, **69**, 279–299.

Strahler, A. N. 1964. 'Quantitative geomorphology of drainage basins and channel networks', in Chow, V. T., (Ed.), Handbook of Applied Hydrology, McGraw-Hill, New York. 439–476.

Wharton, G. 1994. 'Progress in the use of drainage network indices for rainfall-runoff modelling and runoff prediction', *Progress in Physical Geography*, **18**, 539–557.

